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A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART II
TARGET STRENGTH

by

R. J. Urick
Naval Research Laboratory

and

A. W. Pryce
Office of Naval Research

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PREFACE

This report is the second of a series which attempts to summarize existing knowledge about the parameters which appear in the sonar equations. These relationships, which find application in many problems involving underwater sound, are stated for reference in Part I of this series. As outlined in Part I, the objective of the summary is to provide a condensation of some of the basic data in underwater sound for use by practical sonar scientists. The present report deals with the reflection and scattering of sound from targets in terms of the parameter, target strength. Material which could not be included in these confidential reports will appear in a Secret Supplement to the series.

The complete series of reports is listed below:

Part I	-	Introduction (July 1953)
Part II	-	Target Strength
Part III	-	Recognition Differential
Part IV	-	Reverberation
Part V	-	Background Noise
Part VI	-	Source Level
Part VII	-	Transmission Loss

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A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART II - TARGET STRENGTH

DEFINITION

The term target strength refers to the ability of an underwater object to reflect or scatter sound. It is applied to those objects which are targets, that is, to those which in echo-ranging return a portion of the generated sound in the form of a wanted signal. It is essentially similar to the scattering coefficient, 10 log m, which specifies the ability of a unit underwater surface, or of a unit volume of ocean, to scatter sound so as to produce unwanted reverberation.

Target strength is defined to be the ratio, expressed in decibels, of the intensity of the echo, measured at a distance of one yard from the acoustic center of the target in any given direction, to the intensity of the incident sound. In symbols,

$$T = 10 \log \frac{I_r}{I_i},$$

where I_r is the reflected intensity at one yard and I_i is the incident intensity. By acoustic center is meant the point inside or outside the target from which the echo, when observed at a great distance, appears to be radiated — a point located some small distance back from the face of a convex target and in front of a concave one. For many practical purposes the difference in distance between the "acoustic center" and the "face" of the target may be neglected.

In the sonar equations, the target strength of a given target is used with the transmission loss to determine the level of the echo at a certain range. In stating the transmission loss it is implied that a source or an echoing target acts as a point source of sound and radiates spherical waves. Actual targets of finite extent do not behave in this manner, but may radiate effectively cylindrical or plane waves at close distances. This effect of the finite size of the target may be taken into account by correcting either the transmission loss or the target strength; in the literature, it appears that the latter has been done (1). The target strength at short ranges of certain targets under some conditions, such as a beam-aspect submarine, therefore is said to vary with range. A cylindrical target at "beam" aspect has a target strength which increases with range as the first power, out to the limit of the so-called Fresnel region of the target, beyond which the target seems to act as a point source of sound; a plane target has a target strength which increases as the second power of the range at short distances.

Target strength is sometimes defined in terms of the echo-ranging equation as what is "left over" after the echo level is corrected for transmission loss and for the source level of the projector. Another definition could be given in terms of the level of the echo from a sphere (of diameter 4 yd) which has a target strength of zero db. These ways of describing target strength, however, really express methods of measuring this parameter, and do not appear to be as conceptually useful as the definition in terms of the incident and reflected intensities at one yard.

The target strength of a target depends on its orientation or "aspect" relative to the incident beam, and on the direction of observation, that is, the direction relative to the incident beam in which the echo is observed. Thus in its most general use, the orientation of both the target and the direction of observation relative to the incident sound beam must be specified in stating a value for target strength. In normal echo-ranging, however, the same transducer is used for both source and receiver, and the direction of observation is the direction back toward the source. No measurements have been reported of target strengths in other directions,* although the angular dependence of the target strength of submarines, for a fixed aspect relative to the incident sound, is important in some proposed search schemes employing separated sending and receiving transducers.

Since target strength is defined as the ratio of two intensities, it is dimensionless. In radar it is customary instead to use "reflection cross section" as the target reflection parameter which has the dimensions of an area. This quantity is the ratio of the total power reflected per unit incident intensity, on the assumption of isotropic reflection, that is, that the energy reflected in all directions is the same as that in the backward direction. Reflection cross section, σ, measured in sq yd, is simply related to target strength T through a factor of 4π as follows:

$$T = 10 \log \frac{\sigma}{4\pi}.$$

TARGET STRENGTH OF SIMPLE FORMS

For some targets it is possible to obtain a satisfactory value for the target strength by replacing the actual target with a simple geometrical shape for which the target strength is known theoretically. This is all that can be done for targets not yet measured experimentally. Targets for which approximate values can be obtained in this way are those having a single highlight, without re-entrant angles or concave portions, and without numerous sharp protuberances which may contribute appreciable back-scattering to the returned sound. They must also be rigid and immovable in the sound field. There must, obviously, be no penetration of sound into the target with return by its internal structure or composition. Finally, care must be exercised in using the theoretical relationships to make sure that the stated conditions of range, curvature, size, and wavelength are satisfied.

Table 1 gives expressions for the target strength of a few simple geometrical forms. Of the various formulas given, special attention is called to the expression for the target strength of an object averaged over all aspects, a quantity which becomes particularly important in problems like mine hunting where the target aspect can be considered random. This expression relates the average target strength to the total surface area of the target. Like the other expressions in Table 1, it should be used only under the conditions stated in the preceding paragraph. When these conditions are satisfied it is believed to give a target strength value useful in approximate calculations.

TARGET STRENGTH OF SUBMARINES

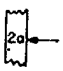
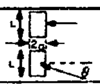
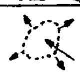
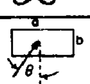
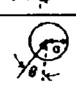
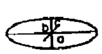
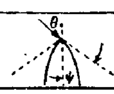
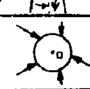
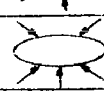
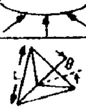
Variation with Type

During World War II, measurements were made on various classes of submarines, such as R- and S-class boats. These small boats were about 185 and 220 ft long and are now obsolete. Since the war attention has been confined to fleet-type submarines, and their modification, the guppies. The fleet-type submarine is very roughly of ellipsoidal shape about

*Some measurements have been recently made by NRL, but the results have not yet been reported (9).

TABLE 1

TARGET STRENGTH OF SIMPLE FORMS

Object		t Target Strength = 10 log t	Symbols	Direction of Incidence	Conditions	Reference
Any Convex Surface		$\frac{a_1a_2}{4\left(1+\frac{a_1}{r}\right)\left(1+\frac{a_2}{r}\right)}$	a_1a_2 = principal radii of curvature r = range k = 2π/wavelength	normal to surface	$ka_1,\ ka_2 \gg 1$	2
Sphere Large		$\frac{a^2}{4\left(1+\frac{a}{r}\right)^2}$	a = radius of sphere	any	$ka \gg 1$	2
Small		$61.7\,\frac{V^2}{\lambda^4}$	V = volume of sphere λ = wavelength	any	$ka \ll 1$ $kr \gg 1$	3
Cylinder Infinitely Long Thick		$\frac{ar}{4\left(1+\frac{a}{r}\right)}$	a = radius of cylinder	normal to axis of cylinder	$ka \gg 1$	2
Thin		$\frac{9\pi^4a^4}{\lambda^2}r$	a = radius of cylinder	normal to axis of cylinder	$ka \ll 1$	4
Finite		$\frac{aL^2}{2\lambda}$ $\frac{aL^2}{2\lambda}\left(\frac{\sin\beta}{\beta}\right)^2\cos^2\theta$	L = length of cylinder a = radius of cylinder a = radius of cylinder $\beta = kL\sin\theta$	normal to axis of cylinder at angle θ with normal	$ka \gg 1$ $r > \frac{L^2}{\lambda}$	5
Plate Infinite (Plane Surface)		$\frac{r^2}{4}$		normal to plane		---
Finite Any Shape		$\left(\frac{A}{\lambda}\right)^2$	A = area of plate L = greatest linear dimension of plate l = smallest linear dimension of plate	normal to plate	$r > \frac{L^2}{\lambda}$ $kl \gg 1$	6
		$\left(\frac{ab}{\lambda}\right)^2\left(\frac{\sin\beta}{\beta}\right)^2\cos^2\theta$	a, b = sides of rectangle $\beta = ka\sin\theta$	at angle θ to normal in plane containing side a.	$r > \frac{a^2}{\lambda}$ $kb \gg 1$ $a > b$	5
Circular		$\left(\frac{\pi a^2}{\lambda}\right)^2\left(\frac{2J_1(\beta)}{\beta}\right)^2\cos^2\theta$	a = radius of plate $\beta = 2ka\sin\theta$	at angle θ to normal	$r > \frac{a^2}{\lambda}$ $ka \gg 1$	5
Ellipsoid		$\left(\frac{bc}{2a}\right)^2$	a, b, c = semimajor axes of ellipsoid	parallel to axis of a	$ka,\ kb,\ kc \gg 1$ $r \gg a, b, c,$	7
Conical Tip		$\left(\frac{\lambda}{8\pi}\right)^2\tan^4\psi\left[1-\frac{\sin^2\theta}{\cos^2\psi}\right]^{-3}$	ψ = half angle of cone	at angle θ with axis of cone	θ ψ	8
Average over All Aspects Circular Disc		$\frac{a^2}{8}$	a = radius of disc	average over all directions	$ka \gg 1$ $r > \frac{(2a)^2}{\lambda}$	6
Any Smooth Convex Object		$\frac{S}{16\pi}$	S = total surface area of object	average over all directions	all dimensions and radii of curvature large compared with λ	5,8
Triangular Corner Reflector		$\frac{L^4}{3\lambda^2}(1-0.00076\theta^2)$	L = length of edge of reflector	at angle θ to axis of symmetry	Dimensions large compared with λ	6

300 feet in length with a beamwidth of 27 ft. Above its deck rise numerous protuberances, such as railings, guns, and an irregularly shaped conning tower—all of which return sound in the reflection or scattering process. In the guppy modification, these protuberences have been largely removed, and a faired housing has been placed about the conning tower.

Although no attempt has been made to investigate the difference in target strength between guppy and fleet-type submarines directly, the reported data seem to indicate that any difference between the two types is small. Because of the "cleaner" superstructure and large, faired conning tower of the guppy boats, it would be reasonable to expect the target strength of guppies as compared with fleet-type submarines to be somewhat less on bow, stern, and intermediate aspects, where scattering presumably plays the dominant role in returning sound toward the source; and that it would be somewhat greater at beam aspect, where specular reflection is important. This, however, is conjecture, since there is no comparative data at all on the two types obtained with the same equipment.

One determination was made of the target strength of the captured German Type XXI submarine, the Ex-U-2008. Its target strength was found to be slightly smaller, by 2 to 4 db, at beam aspect than a fleet-type submarine (USS QUILLBACK), but the absolute values of target strength were stated to be unreliable (10). The British have also measured the highly-streamlined submarine SCOTSMAN, and found an exceptionally low value (12.3 db) for its beam-aspect target strength (11). This submarine is about 220 ft long, and had, at the time of measurement, a very small and low conning tower. No other measurements have come to light on any other modern foreign submarines. No measurements appear to have been made on the new small K-class American submarine.

Variation with Aspect

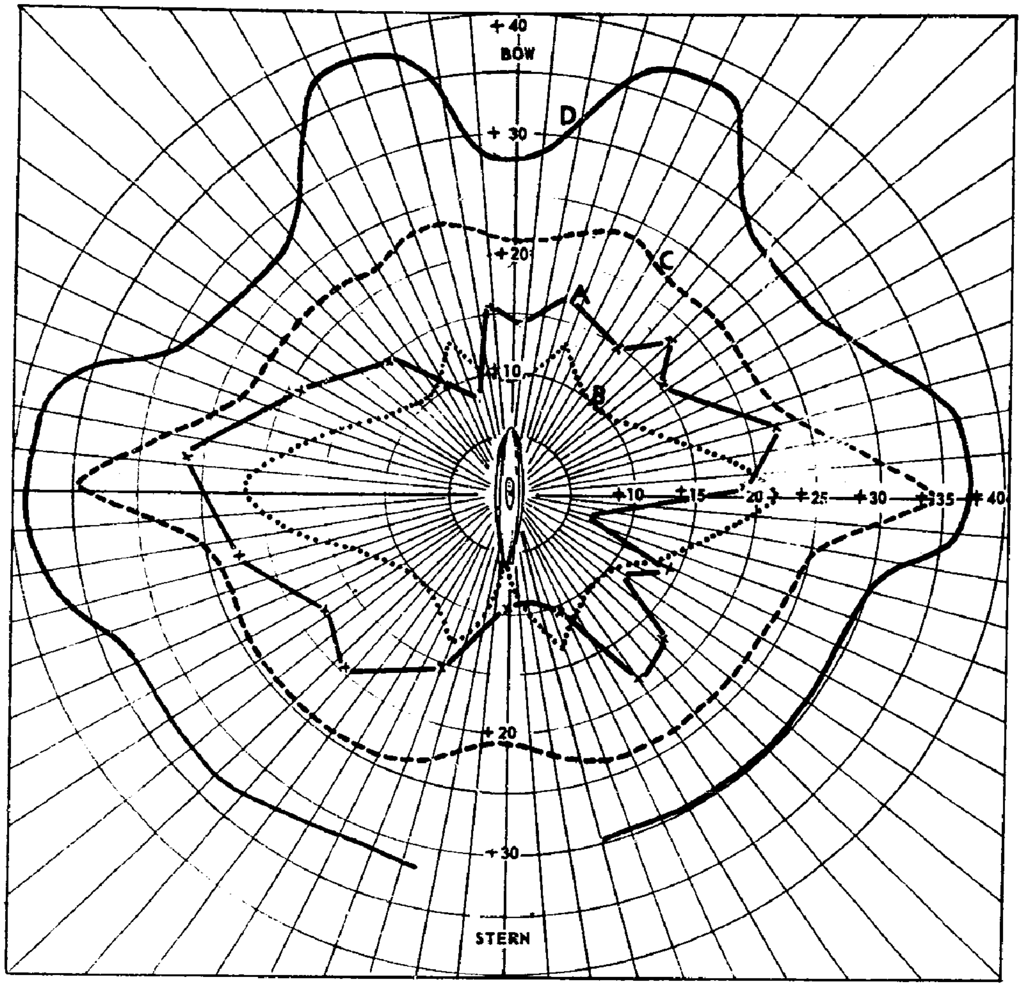
Of all the factors on which target strength depends, aspect angle has received the most attention. It is generally believed that the target strength at beam aspect is higher than at any other aspect, but the amount of increase is uncertain. Indeed, the degree of dependence upon aspect probably varies with pinglength, frequency, and other quantities.

Figure 1 shows target strength plotted against aspect, as determined by several experimenters. Plot A was reported in 1944 by UCDWR (12) at a frequency of 24 kc on an old S-boat; Plot B was determined in 1952 by USL (13) at 25 kc from Project MYSTIC data obtained in 1948 on a guppy submarine; Plot C was measured by NEL (14) at 23.6 kc in 1952 on a fleet-type boat (BAYA); Plot D was found by NRL (15) in 1952 at 10 kc on a guppy. All determinations utilized a pinglength between 20 and 30 ms, except Plot D, which used 100 ms.

Table 2 summarizes the results of recent determinations of the target strengths of submarines at beam, bow, and stern aspects. One World War II value, believed to be the best wartime determination, is also included.

The most striking feature in this table is the great spread of reported values. The lowest beam-aspect value, 12.3 db, was obtained by the British on SCOTSMAN; the highest, 37 db, was obtained on a guppy submarine by NRL using a long pinglength (100 ms) and a rather low frequency (10 kc). Although some of this spread may be attributed to differences in pinglength and frequency, as discussed later, the major portion of it probably represents uncertainty in the field data itself. A determination of target strength requires that the echo level as measured at some distance be converted to the echo level which would exist at one yard, by applying the proper transmission loss. Measurement of the transmission loss for any particular run is a troublesome and vexatious affair which seems to give rise to great uncertainty in all field-determined values of target strength.

It is accordingly difficult to come to a decision regarding a mean or most probable value for the beam-aspect target strength of submarines. If we give all the values listed in



A	UCDWR	S BOAT	24kc	30ms	ref. 12
B	U.S.L.	GUPPY	24kc	25ms	ref. 13
C	NEL	FLEET TYPE	23.6kc	30ms	ref. 14
D	NRL	GUPPY	10kc	100ms	ref. 15

Figure 1 - Some typical reported target-strength vs. aspect plots of submarines

Table 2 equal weight, we find a mean value of 25.6 db. If, on the other hand, we select the better determinations and disregard those of less reliability, we find a higher value, between 28 and 30 db, depending on the choice made; the difference is due to two recent and apparently reliable determinations (14, 15) which yielded high values. During and since World War II, many laboratories have been using 25 db as a working figure for the beam-aspect target strength of submarines. In view of the spread in reported values, there appears to be little reason for choosing an appreciably different figure at this time. As for bow-stern aspect target strengths, it seems futile to attempt to arrive at a reasonable estimate from the data of Table 2.

TABLE 2
Submarine Target Strengths

Target Strength (db)			Frequency (kc)	Ping Length (ms)	Submarine Type	Method	Remarks	Laboratory	Reference	Date
Beam	Bow	Stern								
25 ±4	12.5 ±4	12.5 ±4	24	30	Old "S" Type	Standard*		UCDWR	12	1944
23. 28.7 24 21.4	--	--	15	0.3 1 3	Fleet	Standard using HPSP gear	Large spread in individual values	NEL	16	1950
15.6	8.5	11.5	22	8	Fleet	Cut-on recognition method		P. N. L. Canada	17	1950
35 ±4	21	21	23.6	30	Fleet	Standard	Used an average transmission loss in reduction	NEL	14	1951
27 (?)	--	0 (?)	60	1	Fleet	Standard using Mk 35 echo-ranging torpedo	Torpedo not always pointing at target. Values given are arbitrary averages of highest 1/3 of reported values, and therefore highly uncertain	ORL	18	1951
Upward view ~ 20			60 & 100	0.0.5	Fleet & Guppy	Standard, bottom mounted upward looking ping employed	Values, reported in %, converted to target strength assuming spherical spreading	NOL	19	1951
12.3	-6.3	-6.8	--	--	British "S" class streamlined with low coning tower	Standard		UDE	11	1951
22	9 ±5	5 ±5	24	25	Guppy	Standard (Project-Mystic Data)	Reduction of data somewhat questionable because of hull shielding of transducers	USL	13	1952
37	27	--	10	100	Guppy	Transponder	No knowledge of transmission loss or transducer calibrations required	NRL	15	1952
34.5 ±12.5	--	--	24	30	Fleet	Standard	Note large standard deviation	NEL	20	1952
24	--	--	0.5 - 16	Uncertain of; the order of 1 ms	Guppy	Standard	Octave band analysis of explosive shots	WHOI	21	1952
30	20	--	0.53	100 - 150	Fleet	Standard	Pulsed Fessenden oscillator used as source	NEL	22	1953
24.5	--	--	2.2	25	Guppy	Standard		USL	23	1953
27	--	--	60	36	--	Mk 32 torpedo	Average between 80 and 100 echo levels	NOTS	24	1953

*Standard method involves correction of measured echo levels for transmission loss and transducer calibrations.

When plotted against aspect, measured target strengths form a characteristic pattern, some examples of which are shown in Figure 1. It will be noted that the values of target strength tends to be higher at beam aspect, and at about 20° either side of bow and stern, and to be somewhat lower at bow and stern aspects. The "butterfly pattern" so formed appears to be a characteristic of the reflection processes as later described. The curves shown in Figure 1 again illustrate the wide divergence in reported values of submarine target strengths.

It is interesting to compute values for target strength on the assumption that the echo is due to specular reflection at the outer hull of the submarine. Measurements on ship plans of the radius of curvature in the horizontal plane of the outer hull of a fleet-type submarine at its widest part amid ships (frames 66-72) show it to be about 750 feet and in the vertical plane, 8 ft (25). Using the first expression of Table 1 and assuming perfect reflection at the outer hull, we find a target strength of 22 db. Although it is probably that considerable penetration of the outer hull occurs even at beam aspect, the fact that hull curvature gives a target strength value of the same order of magnitude as the measured values would indicate that specular reflection from the outer plates of the submarine is an important mechanism of reflection at beam aspects.

Some data are available for the target strength of a submarine when the incident sound strikes it at an angle to the horizontal. During the War, a few investigations were made of the variation of target strength with altitude angle, that is, for sound incident from above (26). This would correspond to a downward "look" at the submarine. These old data are adequately summarized in the reference. Since the War, there have been two investigations of the target strength from below. NRL obtained values of target strength by the bottom reflection that are almost the same as those obtained by the direct path (27). NOL reported some measurements with a nearly vertically-upward-directed transducer of a submarine passing over it (19). Echo levels were expressed in this work as a percentage of the level of the outgoing ping at one meter from the bottom-mounted transducer. The strongest echoes had an average level of about 1.8 percent. Converting to target strength by assuming spherical spreading between the transducer and the keel of the submarine 67 ft overhead, the corresponding value of target strength is 20 db, again of the same order of magnitude as beam-aspect target strength.

It should be pointed out that the variation of target strength with aspect is extremely fast and irregular. Measurements by MIT on a scale-model submarine indicate changes of the order of 20 db within less than a 1° change of aspect (28). The smooth plots commonly shown for the aspect dependence of target strength, such as Figure 1, always represent averages over some range of aspect angles; the target strength at some single aspect may be quite different and subject to rapid changes with small changes in orientation.

Variation with Frequency

Most measurements of target strength have been made in the frequency range of operation of standard echo-ranging sonar gear, that is, upward from 10 kc. At these frequencies there seems to be no frequency variation apparent amid the scatter of reported data.

At lower frequencies, NEL has recently made some measurements at 530 cps using a Fessenden oscillator as a sound source (22). A plot of target strength against aspect of the fleet-type submarine BAYA is reproduced in Figure 2. It will be noted that the magnitude of target strength values as well as their variation with aspect are somewhat similar to those at higher frequencies (Figure 1). WHOI has also measured the low frequency target strength of a submarine by using an explosive sound source and by making octave band analyses of the echo (21). It was tentatively concluded that target strengths at all aspects show no marked frequency dependence above about 3 kc, and that below about 3 kc target strengths are lower than at the higher frequencies (except at beam aspect, where they are independent of frequency

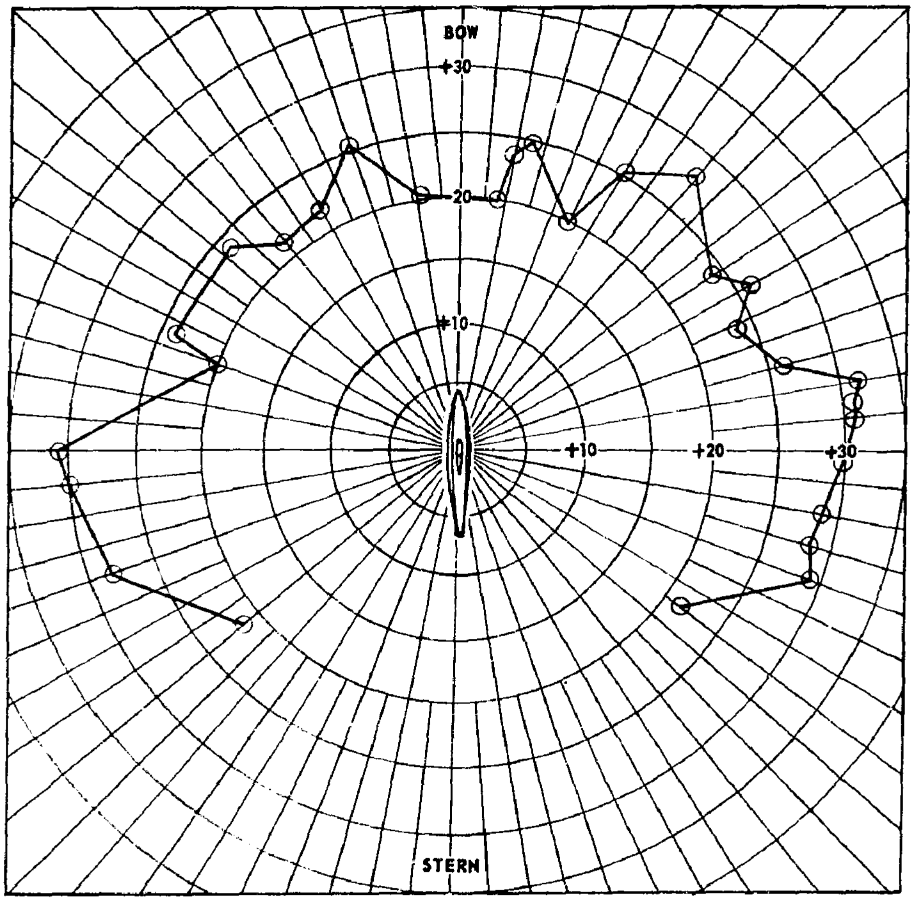


Figure 2 - Target strength at 530 cps for the submarine USS BAYA

down to about 0.4 to 0.5 kc). There was also an indication that below 0.4 to 0.5 kc target strengths fall off sharply at all aspects, although part of this decrease may be due to the use of an incorrect transmission loss. It should be noted that in explosive-source measurements the effective pinglength is uncertain, and varies with frequency. The method is, however, most valuable in that it gives direct information about the frequency variation of target strength on a single ping, and thus for the same propagation conditions. Average values of beam-aspect target strengths within 10° of the beam are as follows:

Frequency Band	Beam-Aspect Target Strength
0.5 - 1 kc	+25
1 - 2 kc	+25
2 - 4 kc	+24
4 - 8 kc	+19
8 - 16 kc	+28

It is likely the internal construction (rib-spacing, etc.) of a submarine is irregular enough for there to be little tendency for any one frequency to be enhanced in the echo (28). No enhancement of the specularly reflected component of the echo would be expected as long as the laws of geometrical optics apply. The matter is, however, of obviously great importance to sonar echo-ranging, and additional systematic searches for frequency peaks in target strength should be undertaken.

At still lower frequencies the whole submarine should exhibit resonances of various sorts. For instance, computations indicate that an ellipsoidal body of the same size, density, and compressibility as a submarine should have a zero-order compressional-mode resonance near 30 cps. An attempt has indeed been made to detect this resonance by means of an active sonar method operating at 30 cps (29), but the results of an analysis of the data have not yet been reported.

NOL has recently done considerable work on the target strength of submarines at frequencies between 60 and 1850 kc with horizontally and vertically-upward directed transducers (30). The results are expressed as the ratio, in percent, of the echo intensity to the outgoing intensity at one meter from the projector. When converted to target strength, however, the results are rendered uncertain because of doubt as to the correct absorption coefficient to apply. As a result, any frequency variation in these data are inconclusive.

In summary, it seems that most of our present information on the frequency dependence of target strength consists of scattered determinations by various observers using different equipment on different submarine targets. No frequency trends of target strength are apparent in these data. Additional specifically designed experiments are needed.

Variation with Pinglength

Figure 3 shows the data of Table 2 plotted against pinglength, without distinction as to frequency or type of submarine.

It would be expected that if specular reflection is the principal reflection mechanism at beam aspect, target strength should be independent of pinglength at this aspect. At bow-stern aspects, where a large portion of the hull is insonified and scatters sound back toward the source by numerous scatterers along the hull, target strength should increase with increasing pinglength until a pinglength is reached such that the entire submarine returns sound at some one instant. That is to say, beam-aspect values should not vary with pinglength, while bow-stern aspect values should increase at the rate of 3 db per pinglength doubled, up to a pinglength of about 120 ms, equivalent to twice the length of the submarine. The data plotted in Figure 3 are inconclusive on this matter, and the plotted points neither affirm nor deny any smooth variation with pinglength.

The best systematic studies of the pinglength made during World War II have been summarized (31). Some of the measurements show a clear pinglength effect; others do not. Nevertheless, it is concluded that "in general, target strength depends on the signal length for short signals although it varies less rapidly than the signal length, or rather, less rapidly than 10 log τ where τ is the signal length; a decrease in target strength is most marked at signal lengths less than 10 ms and at aspects away from the beam."

There has been one post-war report (16) in which values of target strength (obtained incidentally as a by-product of field tests of the NEL high-power, short-pulse equipment) were given for different pinglengths. The values, shown below, are for the beam aspect of the submarine HAYA (SS318) at a frequency of 15 kc.

3.0 ms: 21.4 db
1.0 ms: 28.7 db
0.3 ms: 23.0 db

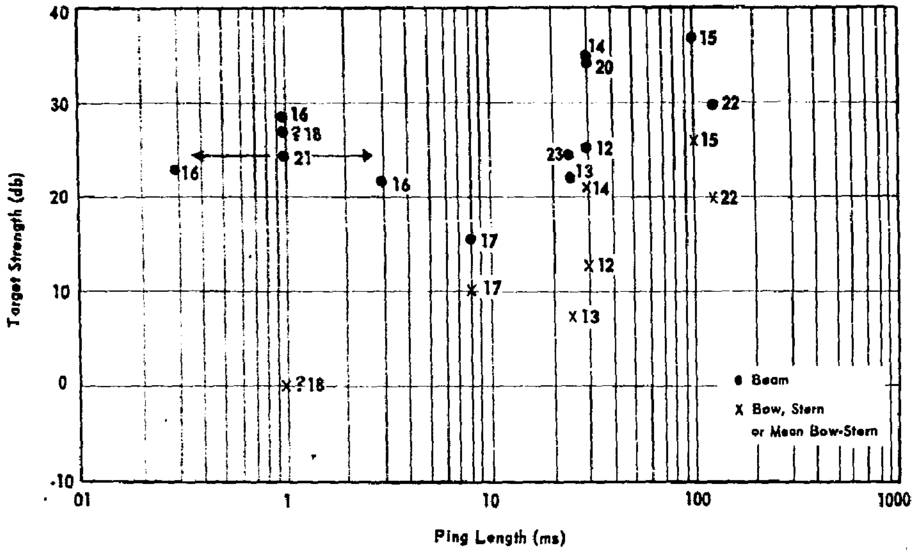


Figure 3 - Pinglength dependence of the target strength of submarines at beam and bow-stern aspects. (Numbers denote document numbers in list of references.)

The variation of target strength with pinglength depends upon whether peak values or average values of echo amplitude are used for the measurement. Peak target strengths are based on measurements of the maximum amplitude of the echo, and often represent a single scattering or reflecting highlight; average target strengths are obtained by reading off the amplitude of the echo at frequent intervals and averaging in such a way as to yield a mean amplitude. Average target strengths are likely to show a greater variation with pinglengths than do peak target strengths.

Variation with Speed

Most measurements of target strength have been made with the target operating at speeds below 5 knots, that is, at speeds so slow that the submarine leaves little or no wake. At higher speeds, when propeller cavitation and turbulence may be expected to produce a large wake, the target strength of submarine plus wake should be measurably higher.

Even on this comparatively simple matter, recent data appear affected by frequency, aspect, and other factors. At frequencies of 60 and 100 kc, using a bottom-mounted pinger, it was found that the magnitude of the wake echo is approximately only one-tenth that of the hull echo at the same range (19). This was corroborated by more recent work over an extended frequency range from 75 kc to 1.8 Mc (30). At such high frequencies, only a small portion of the wake or hull is insonified and returns an echo because of the short range, the narrow beamwidth, and the short pinglength. When all, or nearly all, of the wake is insonified, the wake echo is commonly as strong as, or stronger than, the echo from the submarine hull. For example, the data from Project MYSTIC, wherein thousands of echoes were recorded, show that at speeds of 6 knots or more, the wake echo is stronger than the hull echo (23). Again, it was observed that with QHB sonar on surface ships, torpedo firings tend to be made aft of a submarine target proceeding at moderate or high speeds (23). On the other hand, some British observations of the variation of echo strength with speed of the streamlined submarine SERAPH indicated no speed dependence up to a speed of 13 knots, although it was believed that a change of ±3 db could have been detected (32).

It nevertheless appears well founded that the values of target strength should, for a submarine travelling at 6 knots or more at shallow depth, be increased, perhaps materially, because of the contribution of the wake. The amount of this contribution depends upon a multitude of factors, such as beamwidth, aspect, and frequency. The best theoretical and observational discussion of the target strength of wakes appears in an NDRC Summary Technical Report (33), and this should be consulted for a summary of such exact knowledge as existed at the end of the War. A good deal of additional work on the number and size distribution of bubbles in ship's wakes has since been done by ORL, Penn State, in connection with the development of a wake-following torpedo (34), and NOL has made measurements of the high frequency wake strength of a submarine and its variation with ship speed and depth (35).

Variation with Range and Depth

As stated above, the target strength of a submarine may be said to increase with range at close distances. This is due to the fact that the submarine does not act as a point source of sound, and to the fact that the whole of the submarine may not be insonified by the beam of the projector. Both effects are greatest at beam aspect. Clear-cut field observations, however, appear to be lacking, and there are no post-war investigations of a systematic nature. The best evidence in favor of a range variation of target strengths comes from optical and acoustic measurements on models (36), and from theory. For example, the first equation of Table 1 indicates that, assuming specular reflection from a doubly-curved surface, target strength should increase linearly with range until the range is approximately twice the larger of the two principal radii of curvature. A beam-aspect submarine should have an increasing target strength up to a range of about twice 250 yd, the radius of curvature (25) of the outer hull, in the horizontal plane at its widest part, of a fleet-type submarine. This limiting range should be much less at other aspects.

The depth of a submarine indirectly affects its target strength. The wake of a high-speed submarine is less at depth than it is on the surface, so that the target strength of submarine plus wake should be less also. On the other hand, as the submarine submerges, the sound pressure cancellation effect of the surface is removed, and the apparent target strength would appear to increase. This is more properly an effect on the transmission loss although the apparent strength of the echo will appear to change with depth, especially at low frequencies. The magnitude of these depth effects cannot be easily guessed, and there are no field measurements on which to make an estimate of their magnitude.

The Reflection Processes

A structure as complicated as a submarine can return sound back to the source in various ways. The reflection process that first comes to mind is specular reflection, that is, reflection in the sense that it is used in geometrical optics. Here the amount and distribution in space of reflected energy is determined by: (1) the acoustic impedance of the reflecting surface and (2) its curvature. The acoustic impedance of a submarine for the purpose of computing its target strength is commonly considered to be infinite—an approximation which overlooks penetration of sound into the inner structure of the submarine and which is probably grossly inaccurate at low frequencies. Nevertheless, it appears that at beam aspect, the target strength of a submarine predicted from the curvature of the outer hull is, as mentioned above, in remarkable agreement with measured values. Beam aspect echoes are commonly sharp and clear-cut, duplicating the shape of the emitted ping. It would accordingly be reasonable to conclude that at beam aspect, specular reflection is the principal reflection process. But at other aspects the shape of the echo, and the relatively high target strength compared to what would be expected from the shape of the hull, indicate that other mechanisms are important.

Scattering by small objects, sharp corners, and protuberances is another mechanism by which sound is returned to the source. Examples of scatterers would be the periscope, railings, bits, and in general all other fixtures on the hull having radii of curvature small compared to the wavelength. The elongation of short pings indicates that at off-beam aspects the whole length of the submarine returns sound. Some of this must be small-object scattering.

An important mechanism, recently investigated by MIT (37), may be called structural reflection, that is, penetration of sound through the hull and reflection by the partitions and corner reflections in the ballast tanks. Together with scattering, internal structural reflection appears to be the principal mechanism by which sound is returned to the source. Another mechanism might be termed resonance reradiation. In this category might be placed the phenomenon of nonspecular reflection, wherein a plate of fixed size (such as the outer-hull plates of a submarine) appears to be a perfect reflector at some angle of incidence other than normal. Resonance reradiation would also include the effects of low-frequency resonances in the boat as a whole, such as the first-order compressional mode, or the first-order bending mode. The latter resonance may have been observed in some experiments with accelerometers attached to the hull, which showed a 1.9 cycle shock-excited resonance (38).

The reflection processes have been studied rather thoroughly by a group at MIT (39). From measurements on a carefully constructed 40-to-1 scale model of a submarine, and from theoretical studies, it appears that the aspect plot of target strength should have a

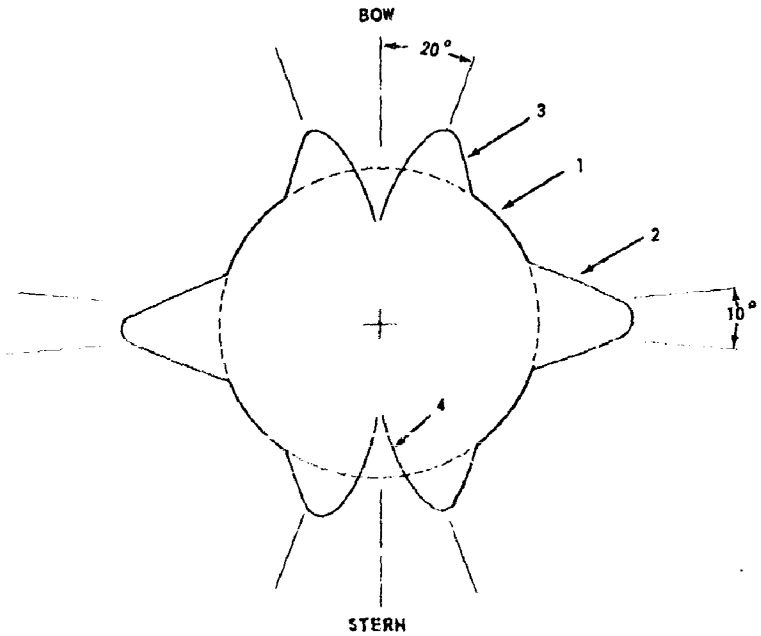


Figure 4 - Idealized aspect pattern of a submarine. (Numbers refer to features described in text.)

typical shape somewhat like that of a butterfly. This "butterfly" pattern, shown in Figure 4, has the following four portions:

(1) a continuous, circular portion, presumably due to the rib structure, edges, corners, etc.

(2) an increase at beam aspect, due to specular reflection

(3) "ears" at 20° either side of bow and stern, possibly due to nonspecular reflection in the outer hull plating

(4) dips at bow and stern, due to shadowing of some of the scatterers by others and to a near-grazing angle of incidence on the hull.

The model used for this investigation had no conning tower, and therefore the possible effects of this structure on the echo were undetermined. Nevertheless, nearly complete agreement was found between the target strength of the model and that of the full-scale submarine (Figure 5) (40).

As shown by the elongation of the echo, at most aspects, the scatterers are distributed all along the length of the hull. For example, measurements of echo length made by MIT on the submarine model show that the time duration of the echo can be accurately predicted from the expression

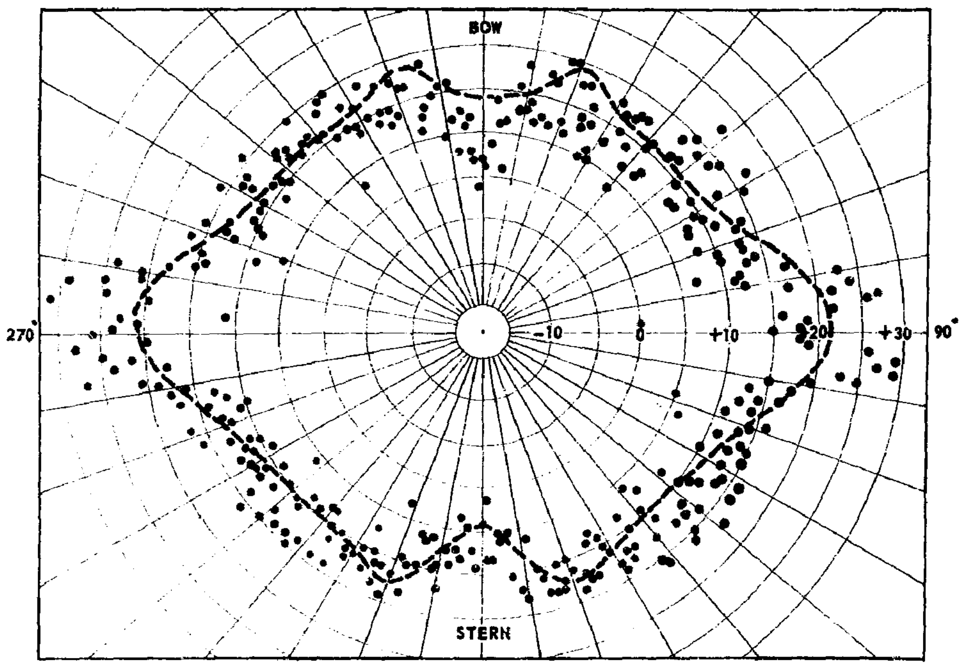
$$E = \frac{2L}{C} |\cos\theta| + P,$$

where E is the echo duration, L the actual length of the target, C the velocity of sound, P the duration of the emitted ping, and θ the angle on the bow or stern (41). Except very close to bow and stern aspects, this has been verified in field measurements as well (42). At some aspects, there are "highlights" in the echo which give it a characteristic shape useful for target classification and estimation of target aspect. Thus, at bow and stern aspects the conning tower forms a recognizable highlight which is the strongest part of the echo. In general, the echo has a complex structure, showing a "blobbiness" of the same length of the ping, which may or may not be characteristic of the target or its aspect.

The complex structure creates some uncertainty as to whether measured values of target strength represent "peak" or "average" values, depending upon whether the maximum amplitude or the average amplitude of the echo was being measured. The difference between peak and average target strengths depends upon the pinglength, being greater for short pinglengths than for long. Whether peak or average target strength are to be used in an echo-ranging calculation should be determined by the display system of the echo being considered; with the ordinary chemical recorder, for example, average target strengths would be more appropriate, while with an "A-scan" oscilloscope presentation of the echo, peak target strengths should probably be used. In published measurements it is often unclear as to which target strength was being measured; it is likely, however, that most published values are peak rather than average target strengths, because of the ease with which peak values can be determined.

TARGET STRENGTH OF SURFACE SHIPS

Because of the lack of interest in applying echo-ranging sonar to the detection of surface ships, much less is known about surface vessel target strengths than about submarine target strengths. An adequate summary of information on this subject as it existed at the end of World War II is contained in an NDRC Summary Technical Report (43), and this information need not be repeated here.



●M.I.T. data for 1/40-scale-model submarine, from R. B. Tatge and R. D. Fay, "Target Strength Measurements on Acoustical Model Submarine," M.I.T. Acoustic Lab. Contract Nobsr 52060, Draft Report, 15 July 1953.

—U.S.L. data from full-scale trial, from H. W. Marsh and M. Schulkin, "Report on the Status of Project AMOS," U.S.L. Report 147, 1952.

Figure 5 - Target strength of a scaled submarine model. The pinglength and frequency used in the model trials were 0.5 ms and 980 kc, respectively, equivalent to 20 ms and 24.5 kc for a full-scale submarine. The U.S.L. data were obtained with a pinglength of 25 ms at 24 kc.

Since that time there has been made but one determination of the target strength of surface ships. In connection with tests of the QHB-1 scanning sonar installed on a submarine, some beam-aspect target strengths at a frequency of 25.5 kc were measured for an EPCE(R) and a destroyer, both travelling at a speed of 5 knots (44). The transmission loss was determined by opening the range in steps from 500 to about 2500 yd. The following values were reported:

E-PCE(R) 855: 17.1 db

DD807: 16.3 db

The standard deviation of these values was estimated to be 2 db.

TARGET STRENGTH OF MINES

Until the last few years, there were no measurements of the target strength of mines. With the development of acoustic mine locators and the increasing importance of being able to locate buried mines, the need for knowledge of the ability of mines to return sound back to the source has become apparent. Information on this subject presented here stems largely from work done at NEL. Additional information of British origin will be included in the Secret Supplement.

Variation with Aspect

The target strength of a mine can be obtained as a function of aspect by measuring its echo level as it is rotated, or by rotating a pinging transducer about a stationary mine. Two examples of the aspect plots of a Mk 26 Mod 1 mine at 10 kc and 100 kc obtained by NEL (45) are shown in Figures 6 and 7.

It will be seen that the greatest target strength of this cylindrical mine occurs at "beam" aspect, that is, at right angles to the axis of the mine. An enhanced target strength is also exhibited at "stern" aspect where a concave face at the end of the mine is presented to the sound beam. Sometimes mines show a peak at "bow" aspect as well. These peaks are superposed on a much lower and highly irregular target strength at intermediate aspects. These features are found for other mines having an essentially cylindrical shape (46).

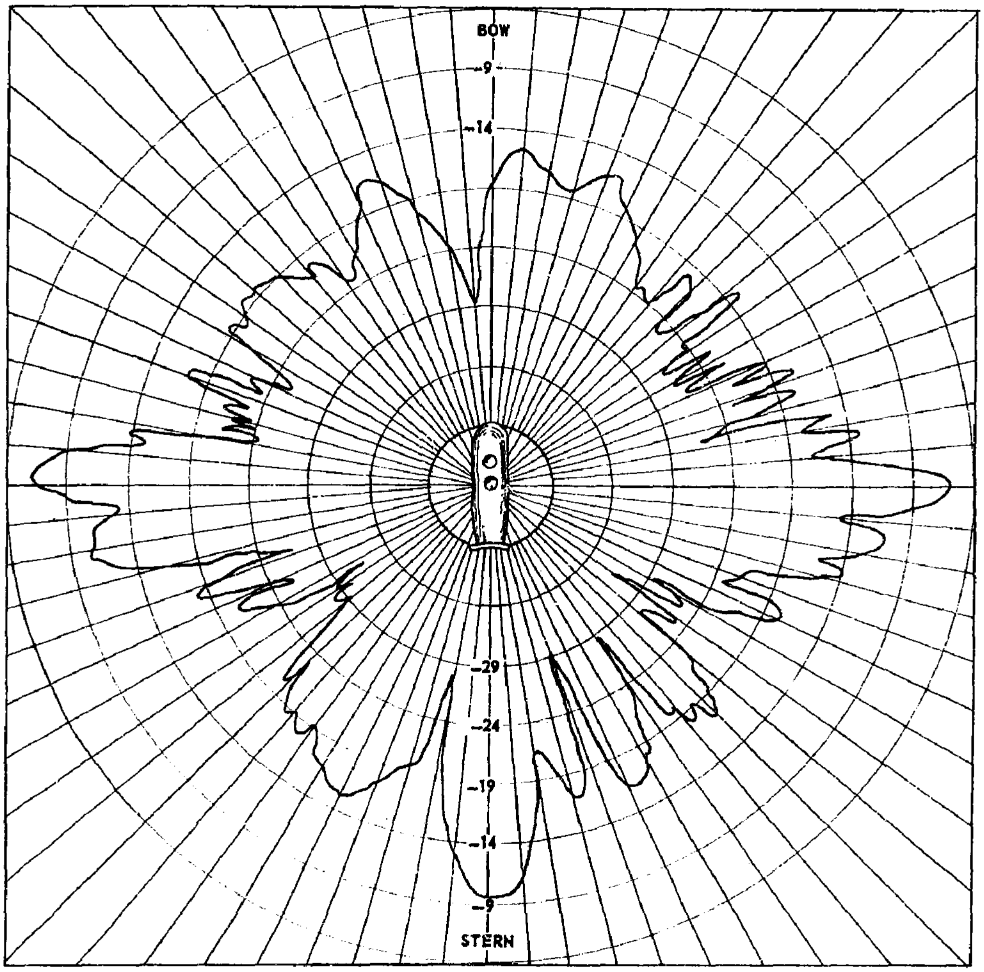
Values of beam, bow-stern, and intermediate aspect target strengths of various mines shown in Figure 8 are given in Table 3, together with the minimum values, which represent the smallest target strength found at any aspect.

It should be emphasized that the maximum values shown occur only within very narrow ranges of aspect angle, and are therefore probably of little operational usefulness. They are values obtained at the testing distance used, and must be increased as discussed below for use at long ranges. Corrections for range of the beam-aspect target strengths have been computed, and the long-range values are also shown in Table 3.

Effect of Range

Reference to Table 1 will indicate that the target strength of a cylinder of finite length in the direction at right angles to its axis increases with range within the Fresnel region. This increase continues out to the range at which the cylinder begins to act as a point source of reflected sound;* beyond this range, the target strength is constant. A similar

*This limit of the Fresnel region is approximately at the range L^2/λ, where L is the length of the cylinder, and λ is the wavelength.



PULSE LENGTH - 2 ms

TEST DISTANCE - 7 METERS

ARMING WELLS PERPENDICULAR TO PLANE OF ROTATION

Figure 6 - Target strength of Mine Mk 26 Mod 1 at 10 kc. (Unpublished data, E. Stewart, NEL, 1953)

condition exists for the reflection from flat plates of finite area, such as exist on the ends of some mines. Since the testing distances used in most of the measurements in Table 3 are within the Fresnel region at beam aspect, a correction equal to 10 log r_0/r_1 (where r_0 is the limit of the Fresnel region for a particular mine and r_1 is the testing distance) is necessary to convert the measured target strengths to their results which involve cylindrical long range values given in column 4 of Table 3.

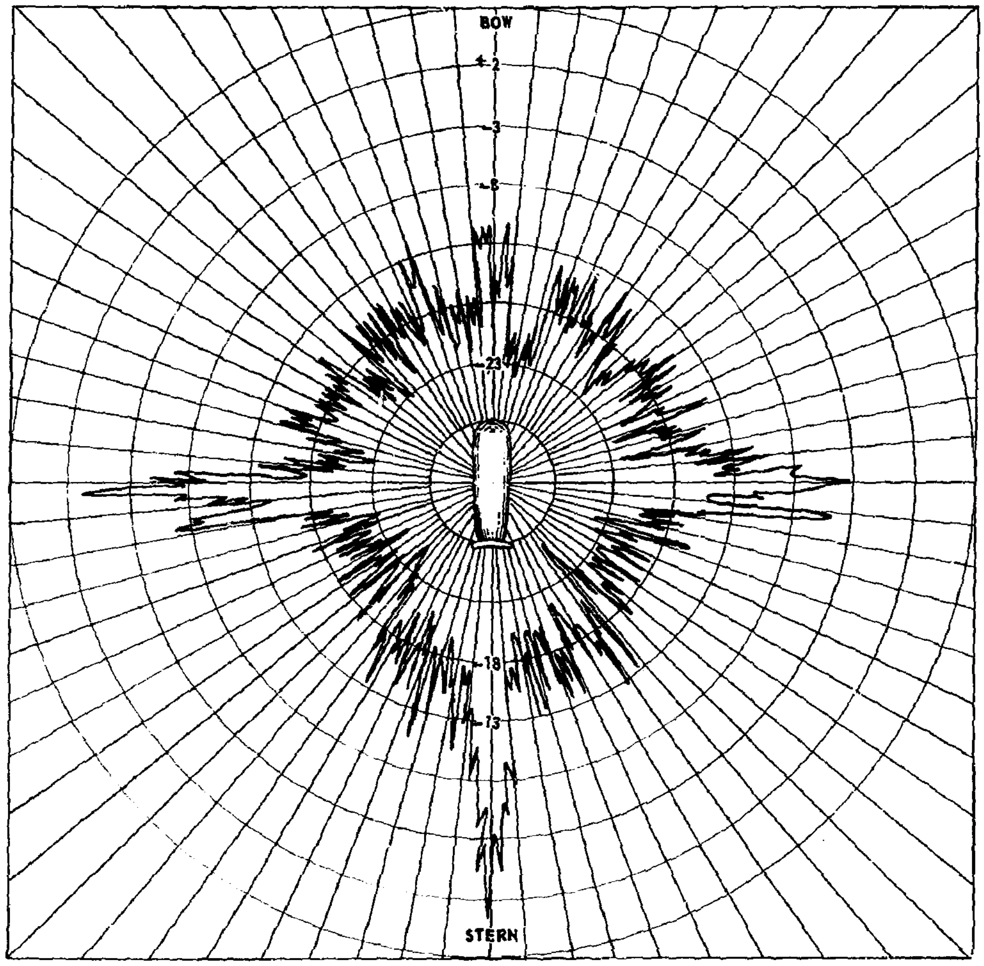


Figure 7 - Target Strength of Mine Mk 26 Mod 1 at 100 kc.
(Unpublished data, E. Stewart, NEL, 1953)

The target strength at intermediate aspects is probably unaffected by range, except at very close ranges. At such aspects, sound is returned not so much by specular reflection as by scattering from protuberances, sharp edges, and the internal structure of the mine.

The effect of range on presently measured target strength is probably therefore that of increasing the target strength of the narrow region around beam aspect. The testing distance is sufficiently great for the values at other aspects to be unaffected by range.

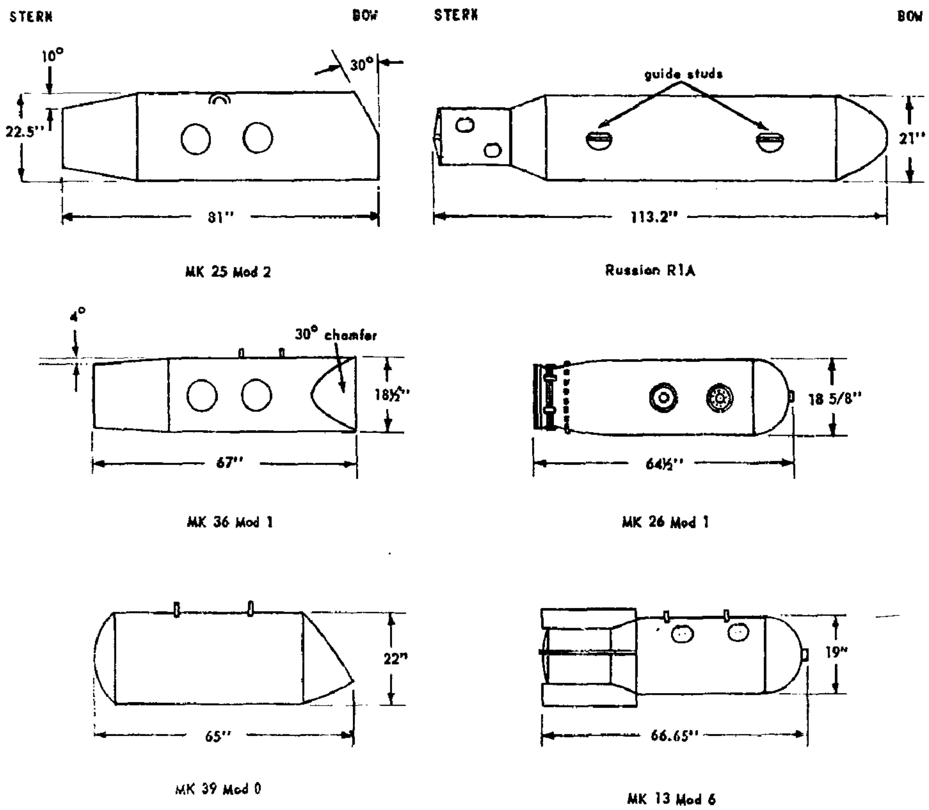


Figure 8 – Drawings of mines for which target strength values have been determined

Comparison with Theory

Table 3 gives computed values of the target strength of various mines at beam aspect, and of the target strength averaged over all aspects, based on the theoretical expressions of Table 1. The agreement with the measured values, reduced to long range, is remarkably close. The agreement at beam aspect implies that the return of sound at this aspect is due, as may be expected, to specular reflection.

Variation with Frequency

A study of the target strength of a mine at three frequencies was made at NEL in 1951 (46). A Mark 25 Mod 2 mine was measured at 76, 100, and 150 kc. It was found that although the target strength of the mine varied tremedously with frequency at any one aspect angle, there was no dependence of the envelope of the aspect plot as a whole upon frequency; changing the frequency changed the details and the irregularities of the target strength plot without affecting its general level.

TABLE 3
Mine Target Strengths

Mine	Over-all Dimensions	Measured Target Strengths					Test Conditions		Computed Values		Reference
		Beam Aspect									
	Length × Diam. (in.)	At Test Distance	Corr. to Long Range	Bow-Stern Aspects	Average at Intermediate Aspects	Minimum Value	Freq. (kc)	Distance (yd)	Beam Aspect	Average Over-all Aspect	
Mk 25 Mod 2	81 × 23	+3	+12	+5	-13	-20	76	16	+13	-11	46
Mk 36 Mod 1	67 × 18-1/2	+4	+11	+8	-15	-23	76	16	+10	-12	46
Mk 39 Mod 0	53 × 22	+4	+11-1/2	+4	-13	-24	76	16	+11	-12-1/2	46
Mk 13 Mod 6	67 × 19	+3	+7	0	-14	-23	76	16	+7	-12-1/2	46
Russian RIA	113 × 21	+3	+13-1/2	+1	-17	-22	76	16	+14	-10	46
Mk 26 Mod 1	64-1/2 × 18	0	+7	0	-18	-25	100	15.3	+10	-13	45
Mk 26 Mod 1	64-1/2 × 18	-6	-6	-10	-21	-30	10	7.6	[illegible]	-13	45
Mk 6	34 diam.	-16 ±3					10-100	-	-	-13	54

A more thorough investigation of this subject has been made more recently at NEL (45). A Mark 26 Mod 1 mine was studied with a pulse length of 1 to 2 ms at intervals of frequency between 5 and 100 kc. An increase of target strength with frequency was found at beam and stern aspects, as shown below, but the mean target strength at intermediate aspects appeared to be independent of frequency.

Aspect	5 kc	100 kc	Change per Octave
Beam	-8 db	0 db	2 db
Stern	-15	-2	3 db
Intermediate	-15 to -20	-15 to -20	not perceptable

Two of the aspect plots of this study are shown in Figures 6 and 7. The testing distances were 7 meters at 5 and 10 kc, and 14 meters at all higher frequencies. The beam-aspect measurement at 100 kc appears to lie within the Fresnel zone, and its value of 0 db should be increased to roughly 6 db to reduce it to a longer range; all other values shown above appear to be substantially long-range values.

When this correction to long range is made, the increase of beam-aspect target strength with frequency of about 3 db per octave is in agreement with that to be expected from theory for a cylindrical target. Interpretation of the stern-aspect variation is complicated by the concave nature of the surface presented at this aspect.

Some peculiar effects were observed during measurements of the target strength of a roughly-spherical Mark 6 mine case (45). With a 1/4-millisecond pinglength, a double structure of the echo was observed, the two pulses being separated by the time equivalent of the radius (not the diameter) of the mine case. Considerable nonuniformity, to the extent of 5-10 db, which appeared in the aspect plot at frequencies near 75 kc, was attributed to irregularities in the structure of the mine case. The average measured target strength was in agreement within the limits of experimental error with the theoretical value of -13 db for a perfect sphere of the same approximate diameter (34 in.). Wartime measurements of the target strength of this object, loaded and waterfilled, at frequencies between 30 and 90 kc at a range of 11.5 ft averaged -8 db (47). Aspect plots exhibited nonuniformity similar to that noted above. Although it was concluded that there was no systematic dependence of target strength on frequency, there was some evidence of an increase with frequency of about 4 db per octave when the case was water filled. Provided the diameter of a sphere is great compared with the wavelength, theory indicates no dependence of target strength on frequency at long ranges. However, this applies only for ideal spheres; actual spheres show erratic frequency and aspect variations resulting from slight irregularities in their form and construction.

At low frequencies, mine cases can be expected to have vibrational resonances where their target strength is high. Such resonances were actually observed by NOL (48) although the details were never given in a formal report. For example, the aircraft-laid ground mines, Mk 36 and Mk 25, were found to have a vibrational resonance between 300 and 400 cps, with a Q of 20; and the extra-strong mine, Mk 39, was found to exhibit a resonance near 600 cps.

Variation with Pinglength

It would be expected that the target strength of a mine should remain constant as the pinglength is decreased, until a pinglength is reached short enough so that the whole of the mine returns sound at some one instant. This pinglength is equal to $2L/c$, where $2L$ is twice the extent in range of the mine and c is the velocity of sound. This effect would be found if scattering occurred from sources distributed over or within the length of the mine, but not if there was a single strong scattering highlight.

Some measurements of mine echo amplitudes as a function of pinglength have been reported for pinglengths shorter than 3 ms, where for a mine seven feet long, a pinglength effect might be expected (49). However no systematic variation with pinglength was found for a Mark 25 Mod 2 mine at a frequency of 100 kc over the range of pinglength 0.1 to 3.0 ms. In these measurements the mine was placed on the bottom. This absence of a strong pinglength effect would indicate that the echo originates within a limited area on the surface of the mine. Studies of the structure of the mine echo, made in connection with these measurements, tend to verify this conclusion as well as do certain model studies on simple cylinders (50).

Reducing pinglength is the easiest method of reducing the reverberation which obscures the echo of a bottomed mine. It is evident that more study should be given to determining the pinglength beyond which it is unprofitable to go in attempting to improve the echo-to-reverberation ratio.

Effect of the Bottom

Many modern types of mine—the so-called ground mines—come to rest, when they are laid on, or imbedded within, the bottom. The presence of the bottom undoubtedly has an effect on mine target strengths, whether due to a Lloyd Mirror effect as the mine rests on the bottom, or to partial burial by the bottom sediments. When a mine is totally buried it is likely that its target strength depends on the surrounding sedimentary medium, which may affect its ability to reflect and scatter sound. A more important effect of the sedimentary environment may well lie in the increased transmission loss which results from absorption in the medium and reflection at the water-bottom. Some scattered observations of the effect of the bottom on mine target strengths have been made. For example, the aspect patterns for cylindrical mines lying on the bottom have been found to be approximately the same as in the free-field condition (51). However, no direct studies of the effect of the bottom on mine target strengths have been made, and not even comparison data for the strength of a mine echo in, on, or above the bottom seem to exist. In view of the very limited data available on bottomed mines, some hesitancy should be felt in applying to such mines existing data obtained under free-field conditions. Even a rough estimate of the amount of a correction to present data must await the results of simple comparison tests and a greater knowledge of the acoustics of the bottom sediments.

TARGET STRENGTH OF TORPEDOES

Much of the data on the target strength of torpedoes* have been obtained in connection with the problem of determining the range of an approaching torpedo by means of active sonar. Most existing measurements have been made at bow aspect, that is, with the torpedo bow-on to the source of sound.

Some early and unpublished work was done on this subject at DTMB (52). The target strength of a stationary torpedo at 175 kc when bow-on was found to be roughly the same as that of a sphere of the same diameter (20") as the nose. This implies a target strength of -17 db.

More recent measurements have been made at NOTS, Pasadena, where a Mk 27 torpedo was supported at its center at the end of a six-inch diameter column, and the target strength measured as a function of aspect at a frequency of 50 kc (24). An aspect plot of the target strength of this torpedo is shown in Figure 9. Rapid changes of target strength with angle were found, which were sometimes as much as 25 db within a fraction of a degree. The values reported, however, are unaccountably high; for example, the bow-aspect target strength is approximately zero db. Contributing factors are believed to have been the plane surfaces of this particular torpedo and some contribution to the echo by the supporting structure.

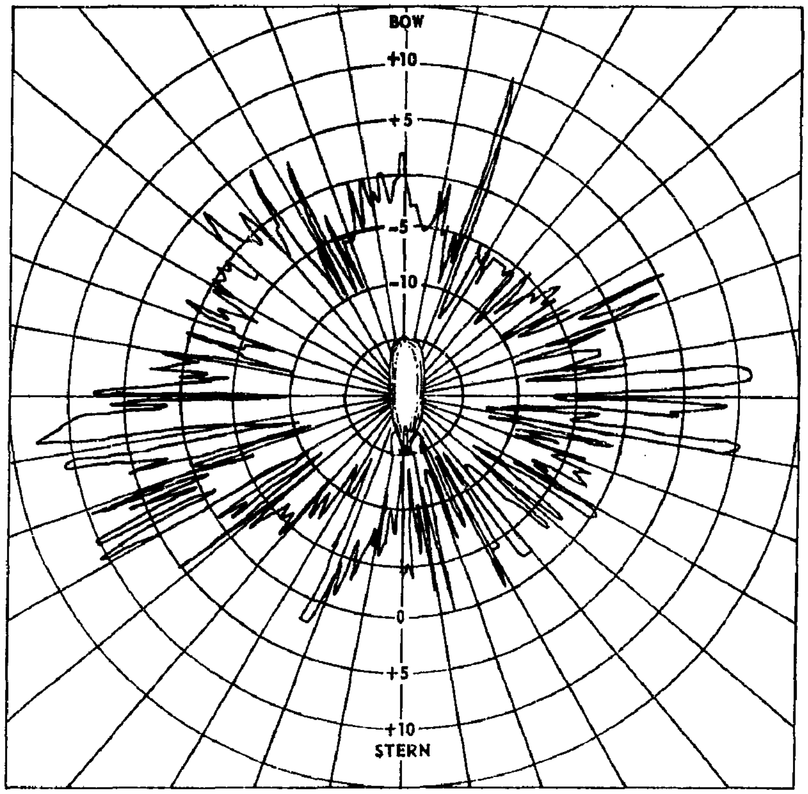
TARGET STRENGTH OF OTHER OBJECTS

Underwater Swimmers

The target strength of a "frogman" was measured at NEL in connection with tests of a sonar system for harbor defense (53). The frogman in his rubber suit, but without his special breathing apparatus, was found at a frequency of 40 kc to have a target strength equivalent to that of a 36-in. sphere (-12 db). On one occasion it was observed that, when a swimmer discarded his rubber suit, his target strength without suit dropped approximately 30 db to about the equivalent of a one-inch sphere (-42 db).

More recent and complete work has also been done at NEL (54). An underwater swimmer wearing breathing equipment has been measured as a function of "aspect." Figure 10 shows the target strength of a swimmer in a vertical position facing toward 000°. His target strength at a frequency of 15 kc is seen to be about -28 db when facing toward the source of sound and -18 db when facing away from it. The higher values in the rear sector can be ascribed to the presence of the three air tanks which the swimmer wore strapped to his back. The low values in the front sector appear to be due to a shielding effect of the body on the air tanks in the rear. No differences were observed when the swimmer made swimming motions instead of remaining stationary.

*The most reliable data on the target strength of torpedoes have been obtained by the British, and will be included in the Secret Supplement.



RANGE 58ft.
DEPTH 40ft.

Figure 9 - Target strength of torpedo Mk 27 at 50 kc. (From NOTS (Pasadena) ltr P8042/HW:jjX25, Ser. 3821 of 15 May 1953 to NRL)

Marine Life and "False" Targets

The target strength of several forms of marine life has been investigated (55) in its relationship to the kinds of organisms responsible for the scattering produced by the so-called "deep scattering layer" in the ocean. The target strength of a certain form of shrimp, a squid, a sea bass, and of a quantity of sargassum seaweed was measured.

Of more immediate application to sonar is the target strength of marine objects which can be mistaken for submarines in echo-ranging search. These "false" targets include whales, schools of fish, underwater reefs, and possibly many other objects in the ocean which can simulate the echo from a submarine. Echoes from such objects have been observed and described many times in a qualitative way (56, 57). However, no quantitative target strength information on false targets exists, although this matter may be of great importance in the target classification problem now being investigated by several laboratories.

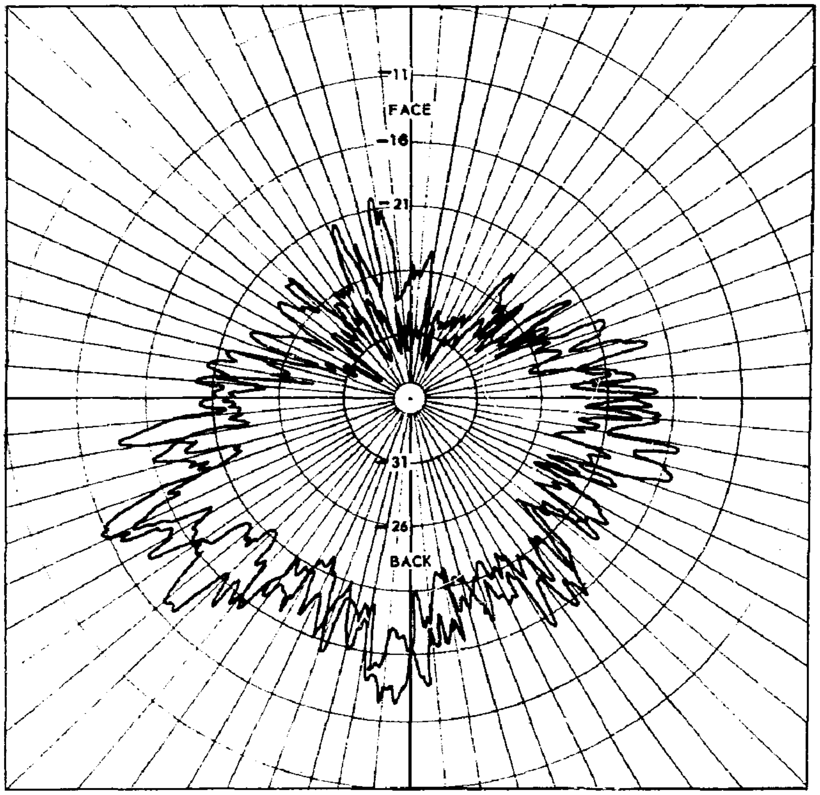


Figure 10 - Target strength of a UDT swimmer wearing breathing equipment. (Unpublished data, C. J. Burbank, NEL, 1953)

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TARGET STRENGTH

An Addendum to Part II of the Summary of Underwater Acoustic Data

R. J. Urick*

Ordnance Research Laboratory
The Pennsylvania State University
University Park, Pennsylvania

and

A. W. Pryce

Office of Naval Research (Code 411)
Washington 25, D. C.

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INTRODUCTION

The term target strength, as used in the Summary of Underwater Acoustic Data (1),† refers to the ability of an underwater object to reflect or scatter sound. It is applied to those objects which are targets, that is, to those which in echo ranging return a portion of the generated sound in the form of a wanted signal. It is defined as the ratio, expressed in decibels, of the intensity of the echo, measured at a distance of one yard from the acoustic center‡ of the target in any given direction, to the intensity of the incident sound. In symbols,

$$T = 10 \log \frac{I_r}{I_i},$$

where I_r is the reflected intensity at one yard and I_i is the incident intensity.

This paper presents additional knowledge and information on the target strength of various objects which have become available since the appearance of the Target Strength Summary (1) in December 1953. This additional information includes, in particular, data on the nonreciprocal target strength of submarines and much additional information on mines, particularly on and in the bottom.

*Now at U.S. Navy Mine Defense Laboratory, Panama City, Florida.
†References appear on pp. 72-74.
‡By acoustic center is meant the point inside or outside the target from which the echo, when observed at a great distance, appears to be radiated—a point located some small distance back from the face of a convex target and in front of a concave one. For most practical purposes the difference in distance between the acoustic center and the "face" of the target may be neglected.

SUBMARINES

As in the past, most of the recent measurements of the target strength of submarines have been concerned with the variation with aspect. Figure 1 gives a summary of a number of recent determinations of the aspect dependence of this parameter. The data plotted here represent measurements at frequencies of 530 cps, 10 kc, and 60 kc, and over the range of ping-lengths from 2 to 500 ms. Included here are the 10-kc target strengths of the fleet types CHIVO and CUTLASS as reported at 10° intervals from 10° to 70° of aspect angles (2) and plotted in the right-hand semicircle; the 60-kc target strength of RAZORBACK (3) plotted in the left-hand semicircle; and measurements of STERLET, CARP, and K-2 by means of the NEL LORAD equipment during one or more complete turns of the target submarine (4). While the general agreement between these various determinations is the most striking feature, some differences

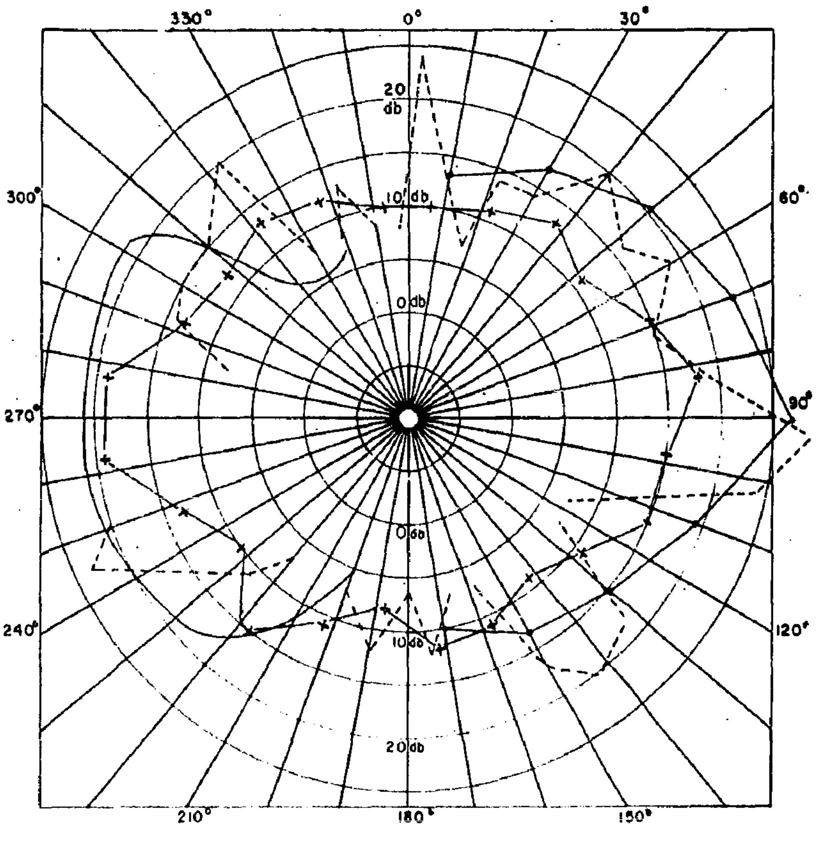

Fig. 1. Recent determinations of submarine target strengths as a function of aspect.

•———• Average of CHIVO (SS-478) and CUTLASS (SS-341). Frequency, 10-kc; pinglength, 0.5-sec; standard method. (NRL data, Ref. 2)

x———x STERLET (SS-392) and CARP (SS-338) averaged in 15-degree intervals. Frequency, 530-cps; pinglength, 300 ms. (LORAD data, Ref. 4)

- - - - - - K-2, one incomplete turn. Frequency, 530 cps; pinglength, 300 ms. (LORAD data, Ref. 4)

———— RAZORBACK, average aspect dependence as measured at ranges of 50 to 100 yards Frequency, 60 kc; pinglength, 2 ms. (Ref. 3) may be noted. The generally higher values for the SSK-class submarine K2, as compared with the fleet types STERLET and CARP, have been attributed to certain differences in shape and constructional details (4). The low target strengths of RAZORBACK as bow and quarter aspects are approached may be attributed to the small pinglength employed in these measurements. But perhaps the greatest source of disagreement continues to lie in uncertainties in transmission loss and the inherent echo-to-echo variability in field determinations of target strength.

In addition to these standard submarines, the target strength of the midget submarine SEEHUND has been given some attention (5). At beam aspect, this craft (39-foot length and 15-ton displacement) was found to have a 25-kc target strength of only 6 ±2 db, while at other than beam aspect its target strength was found to be too low to measure.

It now appears established that the target strength of submarines is largely independent of frequency in the range of 500 cps to 60 kc, without either great "holes" or resonances in the target-strength-frequency curve. This conclusion has been indicated not only by the accumulated results of independent measurements made at various times and with various equipments, but more directly by frequency analysis of explosive echoes (6), and to an extent by model studies (7). For instance, a comparison of the spectrum of the echo with its reverberation over the range of 120 cps to 12 kc indicated no differences between the two that could not be accounted for by propagation effects (8), while other explosive measurements in the range of 630 cps to 10 kc showed no frequency dependence except in the lowest (630- to 800-cps) band, where the echoes were persistently lower (9). Also, USL measurements of submarine target strength at 2.2 kc (10) appear to be essentially similar in magnitude to those made at higher frequencies; an example of measured data on the 2.2-kc target strength of MEDREGAL (SS-480), showing the inherent variability of target strength measurements, is given in Fig. 2. Finally, over a more limited frequency range, recent NRL work shows no difference in target strength between frequencies of 5, 10, and 25 kc (11). Thus, while peculiar effects at frequencies below a few hundred cycles may occur—as has been suggested, for example, by model studies of scattering from compressible cylinders (12)—the present data may be said to verify the essential frequency independence of submarine target strength in the conventional frequency range.

The use of long pulse lengths in echo ranging has established that, at stern and near-stern aspects, the echo from a submarine—and therefore its target strength—exhibits a definite amplitude modulation that is important for target recognition. This was observed during field trials with the NRL 10-kc equipment (13) and has been given detailed study through echo studies

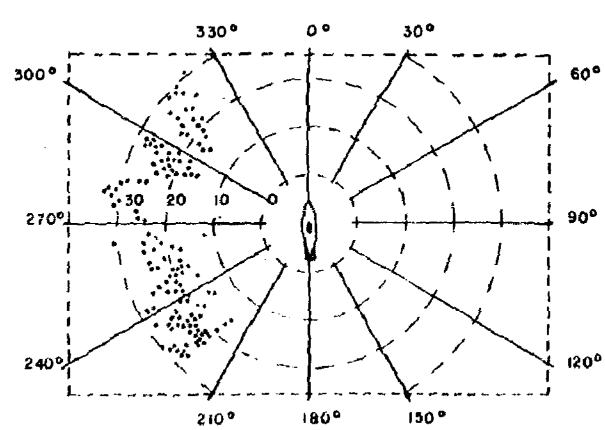

Fig. 2. Target strength (2.2 kc) of the Fleet Snorkel Submarine MEDREGAL (SS-480) at periscope depth. Pinglength unspecified. (Ref. 10)

of a typical submarine propeller (14). In the latter experiments a four-bladed propeller gave a four-lobed patter in the vicinity of "stern" aspect as the propeller was rotated. A maximum target strength of about 0 db was observed as each blade passed into a position of normal incidence, with no variation with frequency between 5 and 45 kc. It might be mentioned in passing that in radar a modulation at the propeller blade rate of the echo from propeller-driven aircraft appears to be well known (15).

The effect of pinglength on target strength has continued to remain essentially unexplored, although our knowledge of submarine echo formation, obtained through experiments such as those with a scaled model submarine hull (16), permit some predictions to be made. If, as seems likely, the submarine at off-beam aspects can be imagined to consist of numerous sound scatterers distributed over the hull, its target strength should increase with pinglength until the pinglength equals, in range, the extension in range of the target; if the submarine presents but one or two strong scatterers or reflectors, as it must at beam aspect, the pinglength variation of target strength should be slight or absent. As indicated in the original summary (1), little conclusive field data is available in this area. In some more recent observations on submarine BANTA an 8-ms echo was found to be, on the average, 7.4 db higher than a 1-ms echo (17). On the other hand, it seems clearly established that echo ranging with a short pinglength can resolve "highlights" at oblique aspects. For instance, records obtained with an Edo echo-sounder mounted horizontally have shown various persistent highlights—such as formed by the end of the pressure hull and the conning tower—at oblique aspects (18). It is of interest to note that during these trials occasional short periods of high target strength were observed that were tentatively attributed to air escaping from the submarine's superstructure. The presence of only a few, discrete, persistent highlights, which varied little over a wide range of aspect angle, was also revealed in tests of a correlation sonar (19).

One major subject concerning submarine echoes is the target strength of submarines in directions other than back toward the source. This has been variously referred to as non-reciprocal or "bistatic"* target strength. Two angles are involved. One angle is that between the now-separated projector and receiver, measured at the submarine, and has been termed the bistatic angle; the other angle involved is the submarine aspect angle, taken now as the angle between the submarine's heading and the bisector of the bistatic angle. These angles are shown in Fig. 3. Measurements of bistatic target strength have been made by USL on the 40:1 scale model previously used by MIT (16) at a frequency of 750 cps, equivalent to a scaled-up frequency of 30 kc if frequency scaling can be assumed (20). At a fixed aspect angle, the target strength of the model averaged in sectors 10° and 25° wide was found to be independent of bistatic angle, as illustrated in Fig. 3. This result would be expected from the manner in which the angles are defined; for example, at beam aspect the projector and receiver continue to lie in the direction for specular reflection as the bistatic angle varies. These model measurements were found to be in agreement with full-scale measurements made at sea by NRL (21). In these sea trials, two surface ships were used in addition to the target submarine DOGFISH (SS-350). The receiving vessel was held, in effect, fixed at an angle of 90° relative to the submarine while the projecting vessel circled the submarine. Both the aspect angle and bistatic angle, as just defined, were continuously changing. Figure 4 shows the average target strength at frequencies of 5, 10, and 20 kc at a pinglength of 200 ms as a function of angle relative to the circling vessel. For this data the ordinary or "monostatic" target strength was arbitrarily taken to be 25 db for all frequencies. Comparable measurements by USL (20) on the scaled model are indicated by the crosses in this figure.

SURFACE SHIPS

No new information has become available concerning the target strength of surface ships and surface-ship wakes.

*This unfortunate term appears to have originated in radar.

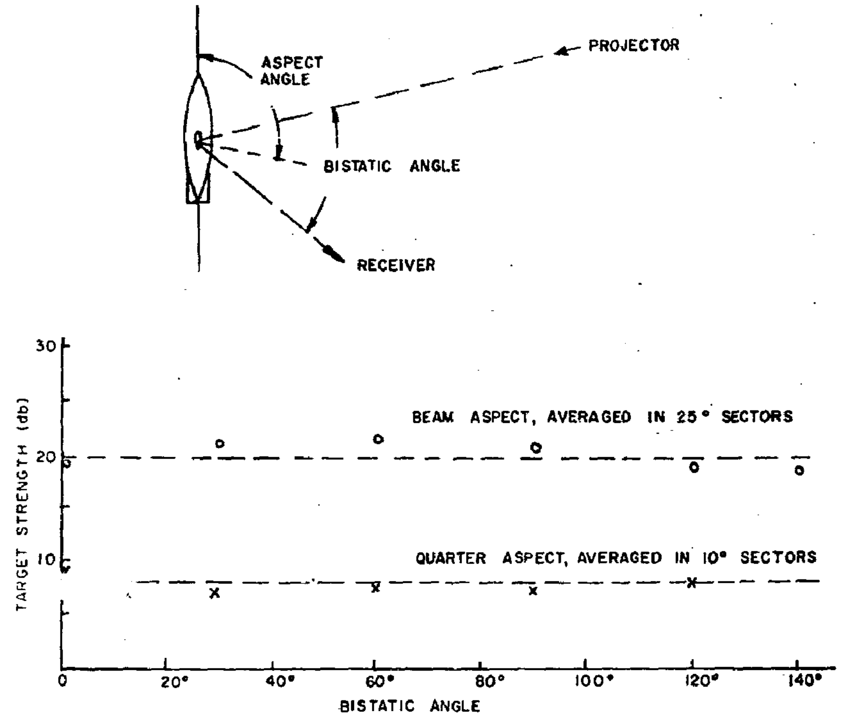

Fig. 3. Variation of target strength with bistatic angle for beam and quarter aspects. Data obtained on 40:1 scale model by USL. (Ref. 20)

MINES

Since the issue of the Target Strength Data Summary, much attention has been given to the target strength of mines. Measurements have been made on the Mk 6, Mk 25, Mk 26, and Mk 36 mines, amongst others, while both pulsed c-w (22) and continuous FM (23, 24) signals have been used. The important areas of new information include measurements of target strength over a wide frequency range and for mines resting on and in the bottom.

The newer measurements tend to confirm the data previously reported (1). For example, the free-field target strength of the Mk 36 has been found to lie between 0 and +10 db at the cardinal aspects and to be between -15 and -25 db at all aspects other than within a narrow angular range about the cardinal aspects (22, 23, 24). Examples of the aspect pattern of this mine as measured with a pulsed c-w and with an FM sonar are shown in Fig. 5. The narrow lobes at the nose, tail, and side have been clearly shown to be due to specular reflection, while the remainder of the pattern is the result of scattering by the various discontinuities of the mine shell. The pattern of the Mk 26 mine is essentially similar, except that the cardinal aspect values are some 10 db lower.

Extensive measurements of the target strength of the Mk 26 and Mk 36 mines over the frequency range from 5 kc to 100 kc have been made at NEL (22). It was found that at aspects where reflection from the ends and sides of the mine occur the target strength increased strongly with frequency at a rate of roughly 3 db per octave. For example, at aspects of 90° and 270°, where a reflection occurs from the cylinderlike sides of the Mk 26 mine, the target strength was found to rise from -9 db at 5 kc to +4 db at 100 kc. On the other hand, its target

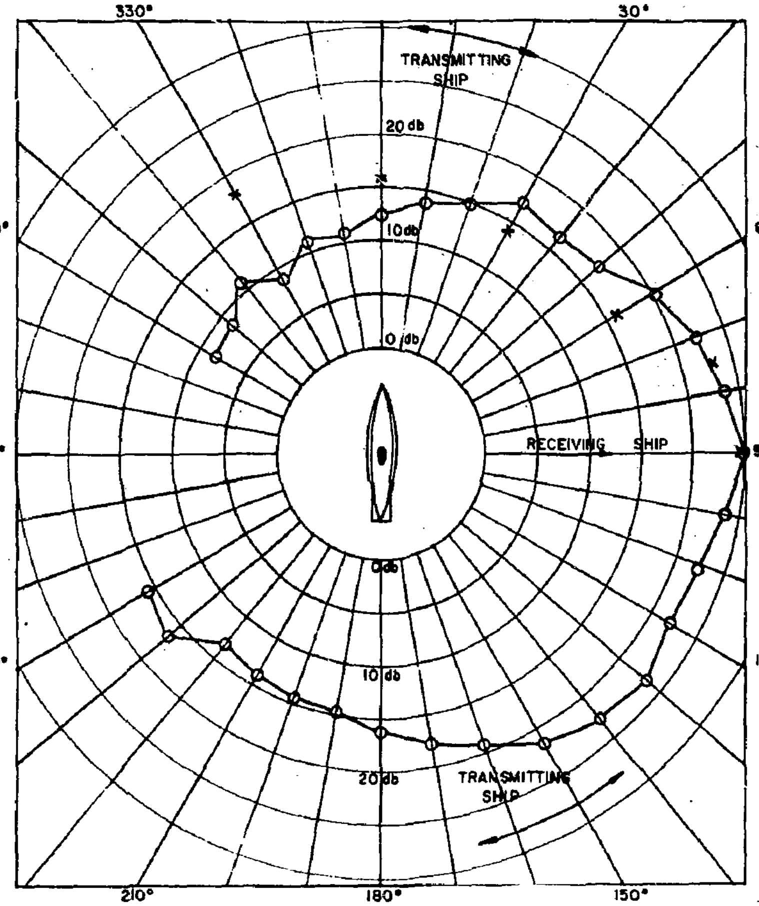

Fig. 4. Nonreciprocal target strength of a submarine. NRL field data on DOGFISH at frequencies 5, 10, and 20 kc averaged (Ref. 21). Crosses show USL model data scaled in frequency and pinglength (Ref. 20).

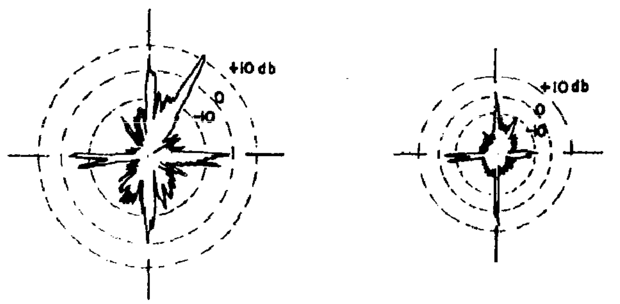

Fig. 5. Target-strength patterns of the Mk 36 mine in the plane of the arming wells as reported by two observers. Left: measured with a c-w sonar at 100 kc; pinglength, 1.5 ms; test distance, 14 meters (Ref. 22). Right: measured with an FM sonar at 75-95 kc; test distance, 78 ft (Ref. 24).

strength at noncardinal aspects, forming the great majority of the directions from which the mine may be viewed, shows only a slight increase with frequency. As a result, the median target strength taken over all aspects shows also only a slight rise with frequency. Figure 6 shows the median target strength of the Mk 26 and Mk 36 mines as a function of frequency from 5 to 100 kc. For this data, the mean target strength (computed on an intensity basis) was found to lie from 5 to 10 db greater than the median values shown in Fig. 6 and to increase somewhat more rapidly with increasing frequency than the median.

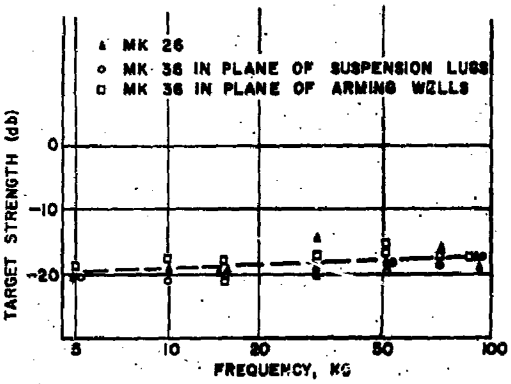

Fig. 6. Median target strength of the Mk 26 and Mk 36 mines as a function of frequency. Test distance, 14 meters; pinglength, 1 and 2 ms (Ref. 22).

Mine target strengths have also been determined for a mine resting on the bottom (24). The aspect patterns of a cylindrical mine on the bottom were found to be very similar to those for the free-field condition, although the measured target strength was slightly less at beam aspects. Partial burying of the mine resulted in only slight decrease in beam-aspect target strength for large grazing angles, but for small grazing angles it was markedly reduced. Presence of the bottom and associated interference effects might also be expected to result in increased target-strength values in some instances. This possibility has been demonstrated in laboratory studies conducted by NEL (25). Measurements for the ideal cases of spheres and cylinders resting on a smooth mercury or sand "bottom" showed variations in target strength of as much as 23 db from maxima to minima as the distance from the bottom surface was varied. These changes of up to 14 db from free-field target-strength values could be explained by interference effects and became less as the reflecting surface was roughened (25). For a mine near, on, or in the bottom, the grazing angle between the incident sound and the bottom is an important additional variable affecting its target strength. Some DRL measurements of the target strength of a Mk 36 mine at "beam" aspect for different degrees of burial are shown in Fig. 7, and the useful histogram for the distribution of target strengths over all aspect angles for the Mk 36 mine resting on a flat sand bottom is shown in Fig. 8. It might be mentioned in passing that the effect of the bottom on mine echoes has given impetus in the past few years to the determination of the velocity of sound in sedimentary materials. A number of NEL reports on this subject have appeared (26-29).

What has been said so far pertains to clean mines uncontaminated by marine growth. However, a mine remaining on the bottom for any length of time may be expected to be covered by marine growth of various kinds that might reduce its target strength to some extent, especially at the cardinal aspects. In one series of trials, a growth of marine animals (tunicates) on the surface of a buried mine was said to have been responsible for much of the difficulty experienced in detection (26). On the other hand, operational trials with the AN/UQS-1 equipment on the detection of growth-covered mines have shown no deterioration of performance compared with newly laid mines (30). This suggests that the effect is small, although no systematic measurements of target strength of mines with marine growth appear to have been made.

Considerable attention has been given to the subject of mine echo formation because of its importance to the problem of echo classification. Both theory and scaled-model techniques have been employed. For example, the reflection of an acoustic step wave from an elastic cylinder, both fixed and free to move in the sound field, has been examined theoretically (31), and a theoretical British study (32) has demonstrated that the echoes are caused by the discontinuities in the target surface, or more specifically, by discontinuities in the rate of change with range of the total target projection seen from the source. Thus, at long pinglengths, the echo may be considered to be the super position of a number of individual echoes of geometrically correct

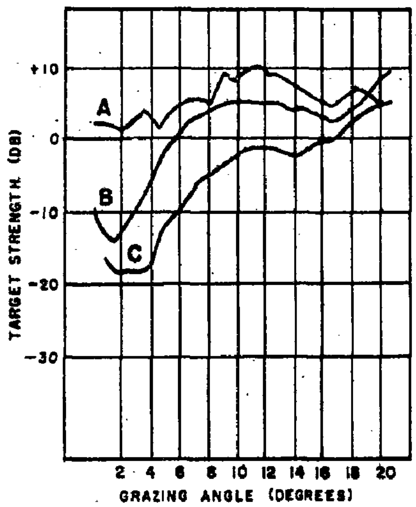

Fig. 7. Variation of Mk 36 mine target strength with grazing angle when (A) on a surface of smooth sand, (B) half-buried, and (C) partly buried with about 8 inches visible above sand. Frequency, 80-100 kc; aspect, 270 degrees. (Ref. 24)

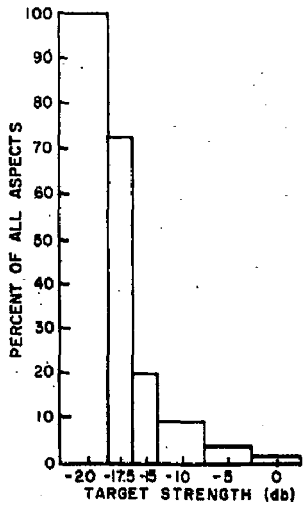

Fig. 8. Histogram giving the distribution of measured target strengths of a Mk 36 mine resting on a flat sand bottom. The ordinate is the percentage of the total azimuthal aspects for which the target strength is greater than the abscissa. Frequency, 78-100 kc; grazing angle, 5 degrees; range of measurement, 78 ft; no Fresnel-zone correction applied. (Ref. 24)

phases and amplitude, each having the envelope shape of the transmitted pulse. Work with an active correlation sonar, having a range resolution of the order of one inch, has indicated that the mine echo at noncardinal aspects is composed of many small echoes from surface irregularities of the order of a wavelength or more in size (33, 34). Thus it appears plausible that, in the design of mines for minimum target strength, the mine shape must be kept as free as possible from irregularities and have a geometrical shape such as to minimize specular reflection. This has been suggested as a more feasible method for the acoustic camouflage of mines than applying anechoic coatings (35). The double-cone and the cube with diagonal vertical have been proposed (35) as shapes to greatly reduce the specular reflection highlights of present designs, and field tests (36) have shown that the target strength of the double-cone is indeed far less at nearly all aspects than that of a sphere of equal volume. In spite of the complexity of its origin, the mine echo appears to be relatively well-defined as compared with nonmine echoes, most of which have been found, through the use of FM sonar, to have multiple peaks and to be of longer time duration than mine echoes (37).

In mine hunting, bottom reverberation normally forms the background in which the mine echo must be detected. Accordingly, the target strength of mines is intimately associated with the back-scattering coefficient of the bottom in most design and evaluation applications of these parameters. Some measurements have been made of the echo-to-reverberation ratio for three typical U.S. ground mines, where, in effect, these two sonar parameters are combined (38). As might be expected, the variation of this ratio with the aspect of the mine is essentially identical to the variation of target strength and has a value that depends upon the pinglength and the type of bottom. The ratio of echo-to-reverberation for a spherical bottom-laid target has been observed (38) to increase by about 6 db in the interval of 1.0 to 0.1 ms for frequencies of 65 and 92 kc.

TORPEDOES

The Target Strength Summary (1) gives a small amount of data on the target strength of torpedoes. To this data must be added some more recent observations of the target strength of a torpedo as a function of aspect (39). In these measurements, a Mk-34 torpedo was suspended at a depth of 200 feet, and the target strength, measured by transducers located at the same depth, was adjusted in aspect by means of a sling. Figure 9 shows the average smoothed result of these measurements. As would be expected, high values near 0 db are observed at "beam" aspects, while target strength was found to be of the order of -20 db at angles other than within a narrow range near beam aspect.

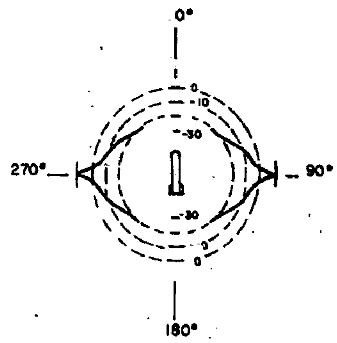

Fig. 9. Summary of measurements of the target strength of a Mk-34 torpedo. Frequency, 60 kc; pinglength, 2 ms; no measurements taken near bow and stern aspects. (Data of Applied Physics Laboratory, University of Washington, Ref. 39)

OTHER OBJECTS

In connection with research on target classification, some information has become known about the target strength of various objects in the sea that might be mistaken for submarines in a sonar search. During a test of various classification devices on the MALOY (EDE 791) in Caribbean waters, USL was able to make target-strength measurements of a number of underwater objects as well as of a submarine with which they might be confused (40). Table I shows some values of the target strengths as observed at sea during these trials. In other measurements by WHOI, a school of 20 to 25 pothead whales, each 10 to 20 ft in length, had a target strength at 12 kc of 0 to -2 db (41), and a fish school was found to have the surprisingly high values of target strength of +19 db at a pinglength of 9.5 ms (41).

Concerning echoes from fish, NOL measurements on single fish (42) have been found to be in agreement with computations made on the assumption that a fish may be acoustically represented by its air bladder. Attention should also be called to an extensive series of British

Table I. Target Strengths (at 25.5 kc) of Miscellaneous Objects

Object	Range of Measured Target Strength, Based on Single Echoes (db)	Pinglength (ms)
Schools of small fish	-41 to -17	6
	-29 to -14	6
	-31 to -12	6
Blackfish and Porpoises	-32 to -11	35
	-30 to -2	35
Shoal in Deep Water	0 to +23	35
Object on Bottom (possibly a wreck)	-12 to +33	6
Submarines	-12 to +34	35
	0 to +27	35

measurements (43) on the echoes from various commercial fish in relation to fish finding and to a good bibliography of echo sounding in fisheries research that this report contains. Other data available on echoes from fish includes information on the spectrum analysis of an explosive echo from one or more blackfish whales, echo 10 to 12 ft long (44).

Minehunting and active-mine actuation have provided an additional stimulus for a knowledge of the echo strengths of marine animals. During a study of echo fluctuation with the AN/UQS-1 mine locator in Chesapeake Bay, numbers of false echoes were obtained that were attributed to schools of fish (45). These echoes, called "angels" in analogy with radar, were found to have target strengths distributed in magnitude as follows:

Number of Angels	Target Strength (db)
2	0 to -5
11	-5 to -10
3	-10 to -15
10	-15 to -20
5	-20 to -25

In another report, the effect of marine animals in causing the actuation of acoustic mine mechanisms was estimated (46). This report contains valuable summary information gleaned from the literature on echo levels from single fish and from fish schools.

Target-strength data for underwater swimmers wearing breathing equipment appears in an NEL report (47). Some of this information was referenced in the original summary.

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DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

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Ser 93/057
20 Jan 98

From: Chief of Naval Research
To: Commanding Officer, Naval Research Laboratory (1221.1)

Subj: DECLASSIFICATION OF DOCUMENTS

Ref: (a) NRL ltr 5510 Ser 1221.1/S0048 of 25 Feb 97
(b) NRL memo Ser 7103/713 of 29 Jan 97
(c) ONR Report "A Summary of Underwater Radiated Noise Data, March 1966"

Encl: (1) ONR Report "A Summary of Underwater Acoustic Data, Part I" AD-030 750
(2) ONR Report "A Summary of Underwater Acoustic Data, Part II" AD-039 542
(3) ONR Report "A Summary of Underwater Acoustic Data, Part III" AD-039 543
(4) ONR Report "A Summary of Underwater Acoustic Data, Part IV" AD-039 544
(5) ONR Report "A Summary of Underwater Acoustic Data, Part V" AD-105 841
(6) ONR Report "A Summary of Underwater Acoustic Data, Part VII" AD-115 204
(7) ONR Report "A Summary of Underwater Acoustic Data, Part VIII" AD-105 842

1. In response to reference (a), the following information is provided:

Enclosure (1) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (2) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (3) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (4) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (5) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (6) was downgraded to UNCLASSIFIED by CNR, 7/29/74; and
Enclosure (7) was downgraded to UNCLASSIFIED by CNR, 7/29/74.

Enclosures (1) through (7) have been appropriately stamped with declassification information and, based on the recommendation contained in reference (b), Distribution Statement A has been assigned.

2. To my knowledge, reference (c) AD-396 737 has not been previously reviewed for declassification. Based on our discussions in April 1997, I am still holding it for Dr. Hurdle's comments.

3. Questions may be directed to the undersigned on (703) 696-4619.

Completed
18 Apr 2000
B.W.

PEGGY LAMBERT
By direction